University of Groningen

The impact of in-vehicle information systems on simulated driving performance

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2009

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Wilschut, E. S. (2009). *The impact of in-vehicle information systems on simulated driving performance: effects of age, timing and display characteristics*. [Thesis fully internal (DIV), University of Groningen, Behavioural and Social Sciences]. [s.n.].

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Download date: 06-05-2023

3 Summary and discussion

3.1 Summary of results

The overall aim of the studies described in this dissertation was to examine the effects of visual IVIS on simulated driving. In the first three experiments the focus was on effects of display complexity. An adaptation of the HASTE visual search task was used as a surrogate IVIS (Carsten & Brookhuis, 2005). Previous research was extended by independently manipulating set size and distinguishing between displays with pop-out or conjunction features, based on feature integration theory (Treisman & Gelade, 1980; Wooldridge, Bauer, Green, & Fitzpatrick). Potential effects of search type and display size on driving were studied using a simulated driving task and a driving simulator. In two of the experiments effects of attention allocation and preparation were studied using ERPs, and in one experiment the use of Head-Up and Head-Down Displays was compared. The second set of experiments focussed on the time course of interference of an IVIS task on critical driving tasks. These experiments were inspired by the PRP effect (Telford, 1931; Welford, 1952). We hypothesized that when the driver interacts with an IVIS while driving there is effectively a short period of dual task performance, so if IVIS information is presented in close temporal proximity with an event in traffic that requires a quick action, for instance an emergency brake, the reaction time might be affected by the processing of IVIS information. A second overall focus was on ageing. In healthy cognitive ageing there is a decline in executive functions (Raz, 2000) which are needed e.g. for integrating information and planning actions. This could effectively put more time-pressure on decision making and increase dual task costs, and hence exacerbate effects of additional information processing load due to IVIS.

3.1.1 Visual search experiments

In the first visual search experiment (section 2.1), we replicated the behavioural results of the visual search task; reaction time increased for more difficult target discriminability and the expected interaction between search difficulty and set size was found. Search time increased especially for displays with difficult target discriminability as the number of stimuli in displays increased. The second experiment (section 2.2) replicated these behavioural results. Further, effects on ERP components were found. The SRN and CNV, which are indicators of search difficulty (Okita et al., 1985) and preparation (Wild-Wall 2007, Falkenstein, 2003), respectively, both showed an effect of more preparation and less negativity related to search load for the easy displays, but not for medium and hard displays. No effects of set size were found. Only the response- and stimulus-locked P3 showed a clear effect of the three target discriminability levels; for the stimulus-locked P3 effects were most likely caused by variations in the latency of the P3 affecting the amplitude. The response-locked P3 is less sensitive to the sources of jitter that can attenuate stimulus-locked P3s. The response-locked P3 showed the same target discriminability effects, but no effects of set size.

In section 2.2 the visual search task of section 2.1 was slightly adapted and used as a surrogate IVIS in combination with a driving task. In this experiment we showed that the complexity of the surrogate IVIS display affects tracking performance. Dual task costs were found even for the easiest search display and increased with search difficulty. Elderly participants showed slower and less accurate performance on single task driving and visual search. Their performance in both driving and visual search task performance worsened most when they had to perform conjunction search with a large set size in addition to the driving task. This effect was mainly visible in the errors elderly committed in the visual search task (48% errors; hence their performance reached chance level). We suggested that the main cause of driving performance decrease with increasing visual search task complexity could be the time that was needed to search the display. Since the IVIS was a head-down display, eyes were off the road during the search for the target. Elderly participants needed more time to perform the visual search task and thus the driving performance decrease could have been directly affected by eyes-off-the-road time. Alternatively, they could have had more difficulty switching between the two locations of interest.

Section 2.3 described a follow-up experiment aimed at further studying the effect of display position. A Head-Up Display (HUD) was introduced to evaluate potential benefits of reducing required eye movements and the possible different effects for different age-groups. Further, we wanted to determine whether the performance decrease described in section 2.2 could be attributed to the time that the participants spend looking towards the head-down display. The results showed that displaying the visual search task on a HUD had a positive impact on performance. Young subjects improved their driving performance while older subjects improved their search performance (error rate). The improvements were mainly visible for conjunction search displays.

3.1.2 Onset asynchrony experiments

Section 2.4 describes a dual-task experiment that studied the time course of interference of a secondary task stimulus on a driving-relevant response. Between 0 and 1600 ms after an IVIS event indicating a possible lane change, subjects had to brake in response to a leading car. Interference was greatest at short SOAs. In the condition in which a lane change response had to be executed, the brake RT was delayed when the SOA between the “lane-stimulus” and braking light of the leading car was short. In the condition in which the participant has to decide that it was not necessary to change lane short SOAs also slowed the brake RT but to a lesser extent. In our interpretation, this was because the correct response – do not change lanes – still had to be selected, but because no subsequent motor response was required the PRP effect was reduced in size.

In section 2.5 a similar time course of interference was shown in a driving simulator. Further, elderly and young participants were compared and the EEG was measured. Again, brake RT was affected by the information processing required by the surrogate-IVIS. Further, brake RT was increased when the SOA between the surrogate-IVIS display and the onset of the brake lights was short, and this effect was stronger for elderly drivers. The target in the surrogate-IVIS display required either pop-out or conjunction search for both young and elderly drivers. At short SOAs, the brake RT was higher after the presentation of a conjunction search display. A rather paradoxical result was found for the elderly drivers that had a shorter brake RT in the lane change condition than in in the keep lane condition. After conjunction displays, drivers reduced driving speed more strongly than for pop-out displays. A stronger reduction of velocity was also found when the surrogate-IVIS indicated a lane change. The ERPs showed age effects for the P3 locked to the IVIS stimuli: the frontal P3 was more enhanced for elderly than young drivers. The amplitudes of the frontal and parietal P3 were not dependent on the surrogate-IVIS task complexity. Trials with a conjunction search display caused the alpha power to decrease for both young and elderly drivers. This reduction was stronger for younger drivers; however, they had higher baseline alpha power than the old drivers.

3.2 Conclusion

The results of the experiments showed how inefficient design of IVIS displays can negatively impact driving performance. While the experiments only used simulated driving, it is likely that the results will hold for driving on the road (Carsten & Brookhuis, 2005). Displays that require attentive conjunction search should be avoided, especially when the number of different objects which need to be inspected is high. Conjunction search increases the search time and thus, especially with a HDD, increases the eyes-off-the road time. The experiment in section 2.3 showed that using a HUD improves driving performance, especially for the young drivers, although there were still dual task costs. In older drivers HUDs showed a smaller advantage, but still reduced the error rate in the conjunction search task. Remaining dual task effects in the HUD presentation could come from the fact that drivers still have to focus their attention on the IVIS ("mind-off-the-road"). This is comparable to research on the use of mobile phones while driving, which showed effects of cognitive distraction and that having a hands free conversation can be as much interfering with driving as with a hand held mobile phone (Haigney & Westerman, 2001).

In all the experiments in which healthy elderly drivers participated (sections 2.2, 2.3, 2.5), detrimental effects of ageing were found. Effects of ageing were found for both the driving performance and the visual search task performance. In the first lane-change task experiment (2.2) the performance on all single tasks was worse for elderly than younger drivers. In the dual task situation in which they performed the lane-change task together with the visual search task elderly drivers showed larger dual task costs on driving performance than young drivers, especially in the error rates of the visual search task. Elderly subjects did not, however, indicate more effort on the subjective rating scale. Elderly subjects showed an increased effect of conjunction search on brake RT and error rates, as well as an increased effect of short SOAs when IVIS events interfered with braking. Especially strong effects of visual search complexity were found in the error rates of the visual search task. ERP data indicated that this was due to elderly subjects investing more effort in preparation for the irrelevant information. Thus elderly drivers are likely to be strongly affected by inefficient design of IVIS displays which require conjunction search and involve large set sizes. This can result in a reduction in driving performance (brake RT) and in the extreme case a breakdown in secondary task performance. If the secondary task is essential, e.g. the driver needs the IVIS to determine where to go, this breakdown will cause subsequent stress as the driver attempts to compensate. Design and evaluation of the quality of IVIS should therefore pay particular attention to this group of drivers.

The use of HUDs is a promising approach to improving IVIS. Dual-task costs, both in terms of driving and secondary task performance, were lowered in young participants when secondary information was presented on a HUD. Elderly drivers showed an improvement with HUD but this was only visible in a reduction of the error percentages. That is, many costs remained, in contrast to other studies on ageing and the usage of HUDs (Gish & Staplin, 1995; Kiefer, 1991). This effect could be caused by the high visual complexity of stimuli, which made the task more demanding compared to previously used tasks. Evidence for such an influence of visual complexity has been found in a driving simulator study (Merat, Anttila, & Luoma, 2005): a systematic increase of the visual complexity of a secondary task caused worse lane keeping behaviour and a greater reduction of speed for elderly drivers than for young drivers. Thus driver age remains an important factor to be considered when designing the display of information on a HUD. It should be considered that even though information presentation on a HUD is more advantageous, it still caused dual task decrements both for young and elderly drivers in this simulated driving task.

The ERP results showed attentional and preparatory effects which were generally more pronounced in elderly drivers; this finding is in line with other studies which also showed an enhancement of cue-locked P3 and CNV in healthy elderly subjects (Falkenstein, Hoormann, Hohnsbein, & Kleinsorge, 2003; Wild-Wall, Hohnsbein, & Falkenstein, 2007). It is also in line with the idea that cognitive ageing seems to be compensated for e.g. by using additional brain regions (Reuter-Lorenz et al., 2001) or a stronger activation of processes also used by young subjects. The pattern of cue-locked P3 and CNV enhancement suggests that elderly drivers increase their orienting to the fixation cross in order to prepare for the upcoming visual search, but only in dual tasks presented via HUD. In single task conditions elderly subjects prepared more intensely for the upcoming visual search task than younger participants. However, the ERPs in the dual task situation indicate a failure of elderly to prepare particularly in the most difficult condition (conjunction search, HDD), and this might be one reason for their performance decrease in particularly that condition.

The stimulus- and response-locked ERP results showed that the usual P3b-analysis for assessing resource allocation in the stimulus-locked data can be misleading. In conjunction search the amplitude of the stimulus-locked P3b was reduced but this was most likely an effect of latency jitter. This could be explained by the large variation of the reaction times in the conjunction condition, since there is evidence that the P3b seems to serve as a mediator between the stimulus and response and is hence more locked to the response than to the stimulus. Indeed, the P3b was clearly visible in the response-locked ERPs under conditions when it was lost using stimulus-locked averaging. Thus the response-locked P3b amplitude may provide a promising alternative measure for resource allocation. A further promising measure for future evaluation of IVIS design is the alpha power, which has the advantage compared to the ERPs that it is less influenced by precise time-locking to an event. Alpha power has already been shown to fluctuate with task demand in applied domains (Schier, 2000; Brouwer et al., 2004; Wilschut et al., 2005). Alpha power was shown to reflect search-related processes, as it differed between pop-out and conjunction search trials. In general, the EEG makes it possible to derive additional information about attention allocation, preparation and task demand without the need for additional probe stimuli.

An important question in simulation studies is always: how do the present results transfer to driving on the road? Concerns have been raised about the reliability and validity of data gathered from laboratory driving tasks and driving simulators (De Waard et al 1991). Several experiments have shown age effects in simulator studies which seemed to disappear in road driving (Schlag, 1993). In the review of Green (2000) differences in brake RTs seemed to increase with ageing, but these results are mainly found for simulator studies and seem to disappear in real road studies. It seems likely that many additional factors come into play in the real world that can compensate for cognitive effects of ageing. However, there are certain advantages of simulated driving research over the real world. First, there is a much higher control over the events and the environment that the drivers encounter. Second, some traffic research might be impossible to perform on the road because it causes too much risk for the participants. Third, it can investigate scenarios and traffic events which are uncommon or traffic scenarios that are based on expectations of real-traffic in the future). As an argument for the transfer of the present results to on the road driving is the controlled study in the HASTE-project (Santos et al., 2005). In this study the effects of visual surrogate-IVIS on performance was evaluated using a laboratory task, a driving simulator and an instrumented vehicle in real traffic. Here, more subtle differences of visual task demand were only found in the driving simulator and in the field, but also in the laboratory task effects of visual demand affected performance, mainly the lateral positioning on the road. Strikingly, in all three settings participants adapted their behaviour when the visual demand of the secondary task affected driving performance (Santos, 2005). Another factor concerning the transfer of the current results to real driving is that in the current experiments static visual search displays were used, whereas real IVIS and HUD are dynamic, updating the information continuously. Research of Kramer & Atchley (2000; in Becic, Kramer, & Boot, 2007) showed that older participants can successfully restrict search to newly added objects to speed search in a static visual search experiment. However, in a replication of this study with a dynamic display by Watson & Maylor (2002), when the target and non-target items were moving across the background, results showed that older participants were not able to selectively prioritise the new objects in a display. This could be relevant for certain types of IVIS were the road environment is displayed and continuously updated from the current car position. This could be a disadvantage for elderly drivers and increase the search time of the displays, if they can not selectively prioritise new information. Further research should use dynamic surrogate IVIS stimuli in addition to driving.

In the introduction of this dissertation, three different strategies were described with which a driver can adapt his behaviour to cope with higher task demand (Bainbridge, 1974; Hockey, 1993). These are investment of more effort, change of working strategy and neglecting information of secondary importance. All these strategies are relevant to the patterns of results found in the experiments. ERP results indicated that older drivers invest more effort when performing the visual search task together with the simulated driving compared to younger drivers. A change in working strategy is often reflected in slower speed, which is an important factor by which a driver can control task demand (Fuller, 2005). However, in the present experiments drivers were instructed to remain at constant speed. It could therefore be that the dual task costs found in the present study were more pronounced than they would be found in real driving where the task demand can sometimes be influenced by lowering speed. However, lowering of speed is not always possible, e.g. in highway situations with heavy two-lane traffic drivers might hesitate to reduce speed. Finally, elderly drivers made many errors in the visual search task in section 2.2 & 2.3. It could be that this was a strategy to cope with the high task demand simply by pressing a button at chance level to be able to attend to the driving task and in that way neglecting a task which has only secondary importance. When difficult conditions of the secondary task are facilitated, such as with HUDs that reduce gaze shifts, secondary task performance in elderly can be improved, but will still interfere with the driving to some extent. Therefore further research is necessary to optimize the IVIS' HMI design as well as to develop validated tests that can define which visual displays are acceptable and which are critical for optimal driving performance.

As was stated in the introduction, the total impact of IVIS on driving is a multi-faceted problem. Besides the dual costs that were found in these studies, which were more pronounced for elderly drivers, IVIS could also have advantages and assist elderly drivers with their coping strategies (Mitchell and Suen; 1997 Davidse, 2005). Future research is needed to focus on the strategies and compensatory mechanisms that drivers adopt to deal with IVIS task demand, especially those strategies adopted by elderly drivers. In particular, effects of dynamic IVIS displays should be explored in dual task paradigms. Also, the relative timing of critical primary driving situations and IVIS stimuli should be systematically varied, as effects are highly dependent on the timing of events.

In conclusion, the dual-task costs of IVIS must be taken seriously, especially in older drivers. These costs can be reduced by taking display characteristics into account, or by using alternative display methods such as HUDs. However, elderly drivers seem likely to remain vulnerable to interference of secondary tasks, such as dealing with IVIS information, on driving. Therefore future studies on in-car HMI must take special account on this group. As shown in the current experiment, EEG may provide useful measures in such studies.